Core Loss Measurement In a Fabricated Stator of a Single-sided Axial Flux Permanent Magnet Machine

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***Abstract*—Core loss prediction and measurement has always been a concern for electrical machine design engineers. In this paper, a method is proposed to measure the core loss in a fabricated stator of a single-sided axial flux permanent magnet machine. The core loss data in the back iron and in a single tooth are measured separately, eliminating the use of any correction factor. The core loss data measured in the fabricated stator is compared with measurements made on an identical toroid to the one from which the stator is fabricated by milling slots, before the milling operation. The purpose of his work is to get the actual core loss as accurately as possible for later loss separation research.**

I. Introduction

Core loss prediction and measurement has always been a concern for electrical machine design engineers especially because of the difficulty of quantifying increased core loss associated with increasing frequency. Steel manufacturers usually only provide 50/60 Hz core loss data, which are not sufficient for accurate core loss prediction at higher frequencies. The American Society of Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC) set several standards for core loss measurements. Generally, there are three test fixtures used in industry: an Epstein frame, a toroid tester and a single sheet tester. In [1]–[3], the authors compare the results from these three testers. It is shown that higher core losses are obtained in a toroid tester compared to an Epstein frame, which is caused by the magnetic damage produced by shearing stresses in a toroid. The drawback of the single sheet tester is that the flux is only measured at the center of strips, which is the same defect as in the Epstein frame. Thus the toroid tester, which approximates the machine geometry is preferred by machine design engineers. The single sheet tester is the least popular and is mainly used for quality control.

With the measured core loss data, a core loss model could be set up to estimate the stator core loss in a fabricated machine. Various core loss models have been developed. The classical equation for hysteresis and eddy current losses is:

$$P = P_h + P_e = K_h f B_m^n + K_e f^2 B_m^2 \tag{1}$$

where P_h is the hysteresis loss, P_e is the eddy current loss, K_h, K_e are the hysteresis loss coefficient and the eddy current loss coefficient, n is an empirically determined constant, often taken as being equal to 1.6, f is the excitation frequency and B_m is the peak flux density. Later research has added a third component [4], which explains the difference between experiment results and the two components above, so we have:

$$P = P_h + P_e + P_{ex} = K_h f B_m^2 + K_e f^2 B_m^2 + K_{ex} f^{1.5} B^{1.5} \tag{2}$$

P_{ex} is the excess loss. K_{ex} is the excess loss coefficient. Recent work, in [5], employs a step-wise approximation for core loss coefficients based on (1). K_h and n are different in certain peak flux density ranges. In [6], [7], curve fitting of the Epstein data by variable coefficients is focused on. The model proposed based on (2) uses hysteresis loss coefficients, which are functions of frequency and induction, and eddy-current and excess loss coefficients, which are functions of induction only. These models are more accurate compared with the typical conventional core loss model with constant coefficients.

However, there is another reason why the measured core loss data produced by a toroid tester or by an Epstein frame might be different from the actual fabricated stator core loss. The properties of steel in the fabricated stator will be changed during the manufacturing process [8]. Reference [9] analyzes potential variations in the performance of the machine caused by the expected variations of the magnetic properties of steel, such as eddy current loss differences due to thickness variation etc. Reference [10] shows that core loss increases due to the punching process, but that an annealing process can remove of this increased core loss, which is also shown in [11]. Different lamination cutting techniques cause variations in losses and in permeability [12], [13]. The electrical design engineer usually bypasses these problems by using corrective coefficients, known as ’building or fabrication factors’ based on the designers experience.

In this paper, a method is proposed to measure the core loss in a fabricated stator of a single-sided axial flux permanent magnet machine. The core loss data in the back iron and in a single tooth are measured separately, eliminating the use of any correction factor. The core loss data measured in the fabricated stator is compared with measurements made on an identical toroid to the one from which the stator is fabricated by milling slots, before the milling operation. The purpose of his work is to get the actual core loss as accurately as possible for later loss separation research.

II. Test Description and Schemes

A. Description of test stator cores

A single-sided axial flux permanent magnet machine was designed as an integrated starter-alternator for use in a series hybrid vehicle. The specifications for the stator are: 24 slots, 22 poles, outer radius 98 mm, inner radius 58 mm, slot depth is 35 mm, slot width 8 mm, stator back iron thickness 10 mm. It has single layer non-overlapped windings. The steel grade of the stator is non-grain oriented M12-29G from AK steel.

There are three tests. First, the core loss measurement is carried out on a toroid stator core prior to milling the slots. The second test is to measure the core loss in the back iron of a slotted stator with an excitation current winding around the back iron. The third test is to measure the core loss in a single tooth with an excitation current winding around only one tooth. The details of the tests will be presented in Section III and Section IV.

B. Test scheme

Fig. 1. shows the test scheme. The function generator, LFG-1300s, provides a sinusoidal voltage at different frequencies and amplitudes. Here the measured frequencies are from 60Hz to 500Hz. The audio amplifier, Lanzar MAXP2960N, is used to amplify the sinusoidal voltage from the function generator and provide a current drive. It can provide a maximum power of 600 W (RMS continuously into 4 ohms) when the 2 channels are bridged. The high power audio amplifier is relatively easy to obtain and costs only a few hundred dollars. A current probe and a differential voltage probe are used to measure the primary exciting current and secondary voltage.

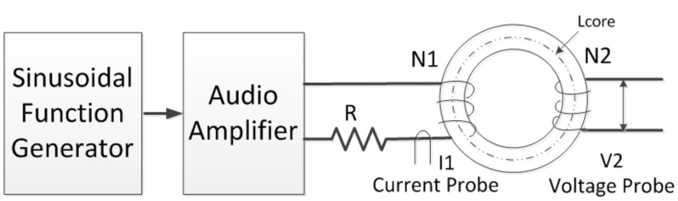


Fig. 1. Test scheme for core loss measurement

The magnetic core has two windings. The primary winding is used to create a magnetic field intensity H, which is:

$$H(t) = \frac{N_1 \cdot I_1(t)}{L_{core}} \tag{3}$$

in which L_{core} is the average magnetic flux path. The flux density is:

$$B(t) = \frac{1}{A_{core} \cdot N_2} \int V_2 dt \tag{4}$$

A_{core} is the cross section area of flux linkage. In measuring core loss, it is assumed that all excitation power is absorbed as core losses, indicating that there is no secondary current. These are good assumptions since the secondary side voltage probe draws no current due to its high impedance [14]. It is also assumed that the flux flowing into the magnetic core is equal to the flux linkage in the primary winding, which means that the flux flowing in the free space around the toroid evaluates to zero. The detailed calculations can be found at [15]. These assumptions can also be checked in 3-D FEA. The measured core loss is calculated as:

$$P_{coreloss} = \frac{1}{T}\frac{N_1}{N_2}\int_0^T V_2 \cdot I_1 dt \tag{5}$$

T is the period of the waveform. If written in sampled data is:

$$P_{coreloss} = \frac{N_1}{N_2}\frac{1}{K}\sum_{k=1}^{K} V_2[k] \cdot I_1[k] \tag{6}$$

K is the number of samples in one period, N1 is the number of turns in the primary windings, N2 is the number of turns in the secondary windings.

III. Core Loss Measurement in Unslotted Toroid

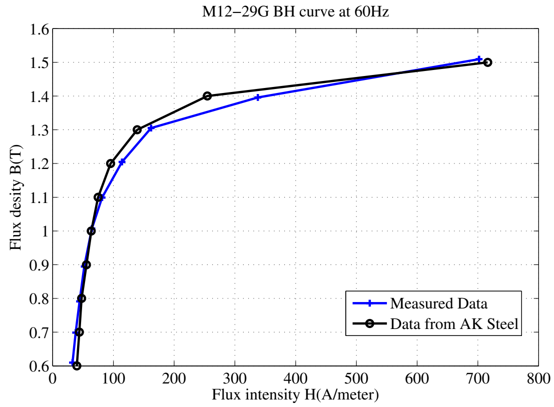
A. Test verification at 60 Hz compared with steel manufacture data

The test system is set up according to Section II. The unslotted toroid stator is shown in Fig. 2. In order to validate the accuracy of the system, the core loss measurement at 60 Hz is performed and compared with the only available data from the steel manufacturer. From Fig. 3(a) and (b), good agreement between the measured data and the original data from AK steel can be seen.

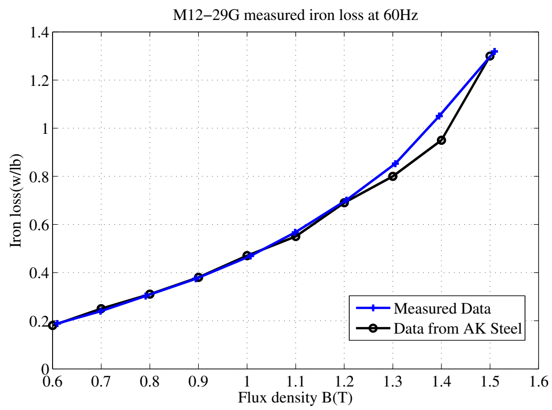
Fig. 2. Unslotted toroid for core loss measurment

B. Test results at frequencies (60 Hz, 100 Hz, 200 Hz, 300 Hz, 400 Hz, 500 Hz)

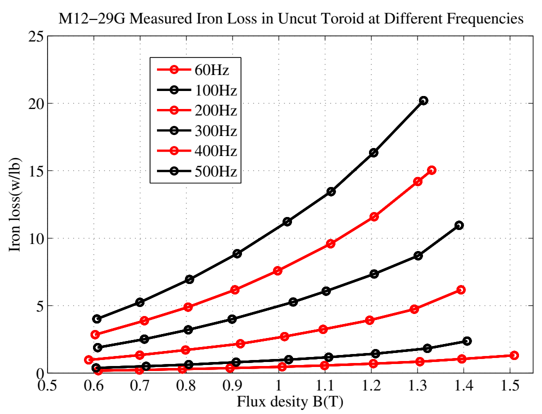
Fig. 3(c) shows the core loss at other frequencies.



(a)



(b)



(c)

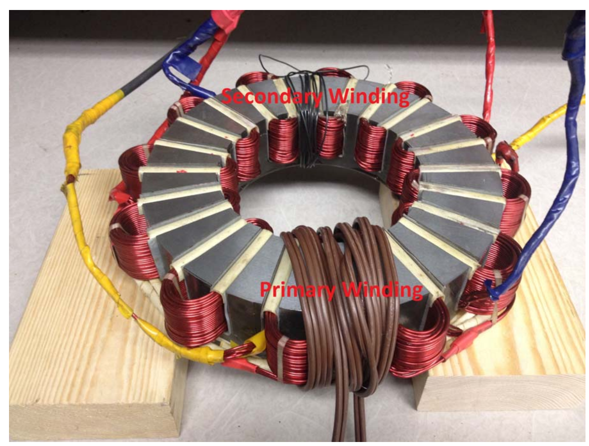
Fig. 3. M12-29G core loss measurement in unslotted toroid at 60 Hz

IV. FEA Simulations and Core Loss Measurement in the Back Iron

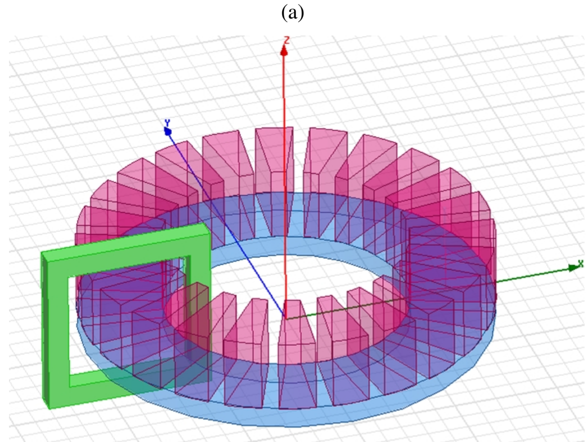
Measurements on the fabricated core will attempt to estimate separately the core loss in the teeth and in the back iron. The flux linkage direction in back iron is parallel to the rolling direction of steel, however the flux linkage direction in the teeth is across the rolling direction. Although the electrical steel used M12-29G is classified as non-grain oriented steel, anisotropy might still exist. Moreover, the milled edges in the tooth could increase the core loss.

A. FEA simulations for back iron core loss measurement

A 3-D FEA model is set up as shown in Fig. 4(b). The excitation current in the primary winding sets up the flux linkage in the magnetic core. In the FEA model, the secondary winding is ignored. This test is similar to the test of the unslotted toroid. However, the flux linkage shown in Fig. 5 indicates that there is flux flowing up in to the tooth as it passes under a tooth. Thus in the experiment shown in Fig. 4 (a), the measured core loss will include the loss in the teeth, which needs to be computed and subtracted. The core losses in different volumes can be calculated separately in the FEA. The FEA results are shown at a 60 Hz sinusoidal current excitation in Fig. 5 (c). The red line is the total core loss, the blue line is the core loss in back iron, the green line is the core loss in the teeth. The loss in back iron accounts for 92% total loss. The purpose of the FEA is not to attempt to establish the actual level of core loss, but to establish a ’split’ to apply to the single measured loss number, to isolate the losses in the back iron alone. This number does not change with frequencies and flux densities in FEA simulation results.

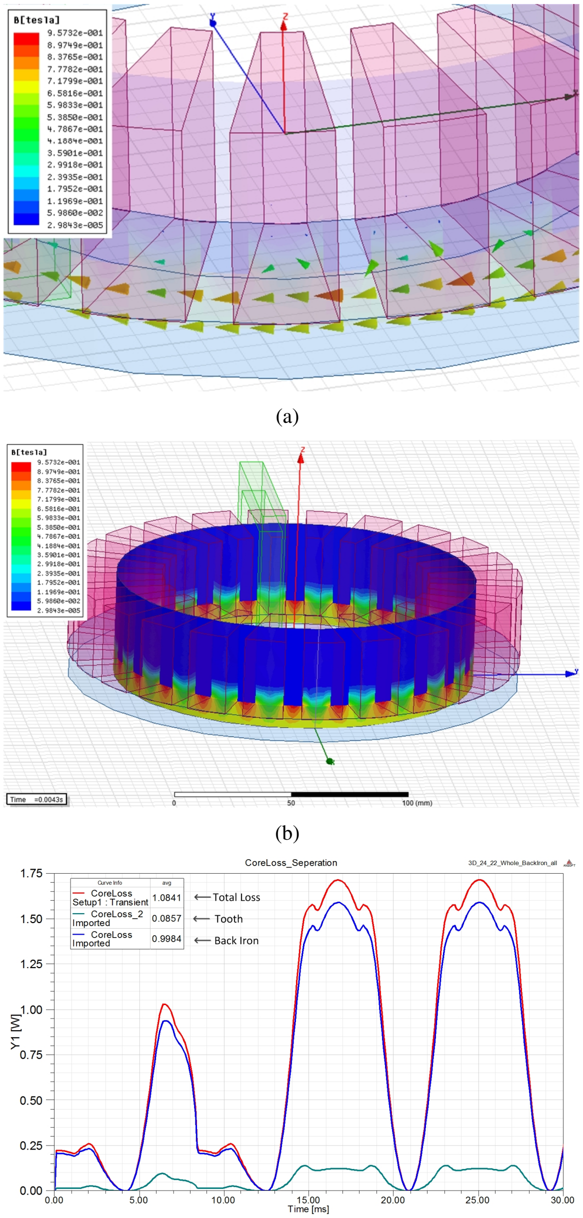


(a)



(b)

Fig. 4. Core loss measurement in the back iron (a) Experiment (b) FEA model



(a)

(b)

(c)

Fig. 5. Flux distribution in the back iron and in the teeth and Loss separation result

B. Experiment results for back iron core loss

The experiment result of core loss in the back iron at various flux densities is shown in Fig. 7. The detailed data are shown in Table. I. It can be seen that the back iron loss is close to the core loss measured in the unslotted toroid.

V. FEA Simulations and Core Loss Measurement in the Teeth

A. FEA simulations for the teeth core loss measurement

A 3-D FEA model is set up as shown in Fig. 9. The excitation current in the primary winding is only implemented in a single tooth. The unslotted toroid is put on the top of

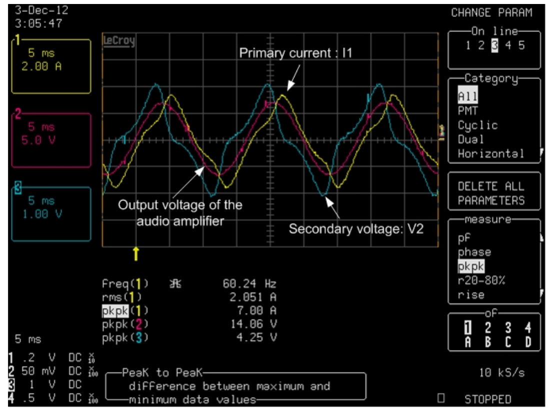


Fig. 6. Measured primary current and secondary voltage at 60 Hz and 1.0 T

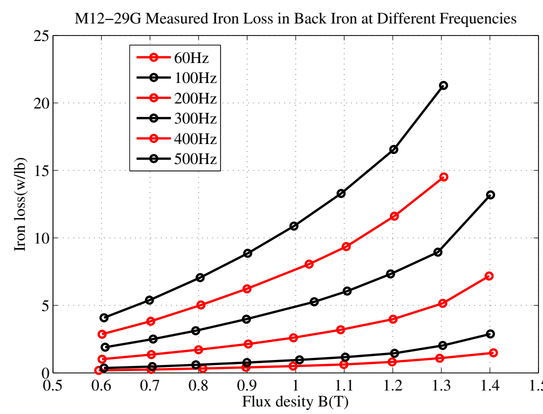


Fig. 7. Estimated core loss data with 92% split in back iron at different frequencies

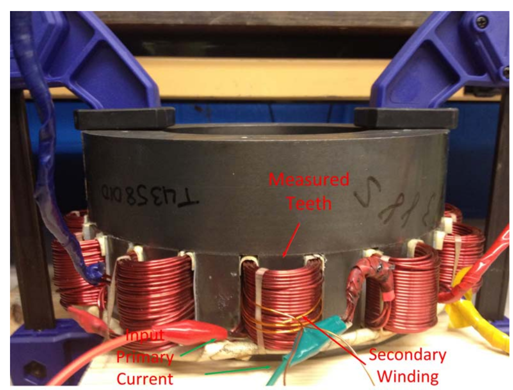


Fig. 8. Experiment for core loss measurement in a single tooth

the finished stator to close the flux linkage path. The mating surfaces were ground to provide the minimum possible air gap. The FEA core loss separation results are shown in Fig. 11. It can be seen that the single tooth loss accounts for 55% of the total loss measured at 60 Hz sinusoidal excitation current. This number will be used to separate the loss in the single tooth only, since experiment measures more than the material of one tooth alone. This number does not change with frequencies and flux densities in FEA simulation results.

TABLE I
MANIPULATED MEASURED LOSS DATA OF M12-29G

M12-29G Iron loss																		
*from left to right are losses in Unslotted Toroid, Back Iron (with 92% split) and Teeth (with 55% split) Unit: (watt/lb)																		
B(T)	60 Hz			100 Hz			200 Hz			300 Hz			400 Hz			500 Hz		
0.6	0.19	0.18	0.46	0.38	0.36	1.53	0.98	1.01	3.50	1.90	1.90	5.43	2.85	2.87	8.11	4.01	4.08	12.19
0.7	0.24	0.24	0.82	0.51	0.46	1.89	1.34	1.35	4.78	2.52	2.50	7.36	3.88	3.83	11.49	5.25	5.38	16.18
0.8	0.30	0.32	0.82	0.63	0.59	2.34	1.71	1.71	6.07	3.21	3.11	9.60	4.90	5.03	14.55	6.94	7.05	20.91
0.9	0.37	0.40	1.08	0.81	0.76	3.24	2.18	2.13	7.25	4.00	3.98	12.39	6.17	6.23	17.96	8.86	8.86	26.23
1.0	0.47	0.49	1.35	0.99	0.96	3.71	2.71	2.60	8.70	5.27	5.26	14.91	7.58	8.06	22.41	11.22	10.87	31.97
1.1	0.57	0.62	1.58	1.18	1.16	4.03	3.24	3.19	10.18	6.08	6.05	21.00	9.59	9.36	26.95	13.46	13.29	39.16
1.2	0.70	0.81	1.99	1.44	1.45	4.69	3.92	3.98	12.56	7.35	7.32	26.89	11.60	11.61	33.24	16.34	16.55	N/A
1.3	0.85	1.08	2.47	1.83	2.02	5.48	4.74	5.15	14.87	8.70	8.93	34.1	14.20	14.51	40.55	22.21	21.30	N/A
1.4	1.05	1.48	2.87	2.37	2.88	6.20	6.17	7.18	18.14	10.95	13.18	46.66	N/A	N/A	N/A	N/A	N/A	N/A

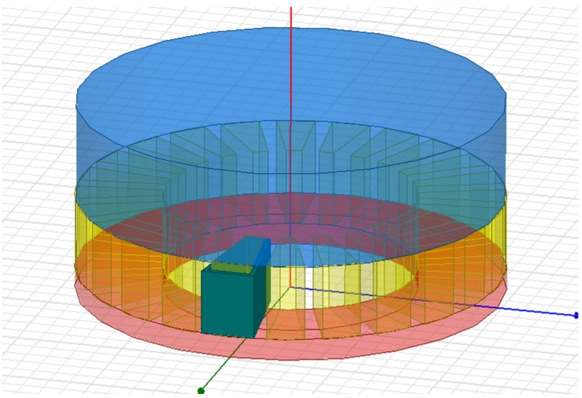


Fig. 9. FEA model for core loss measurement in a single tooth

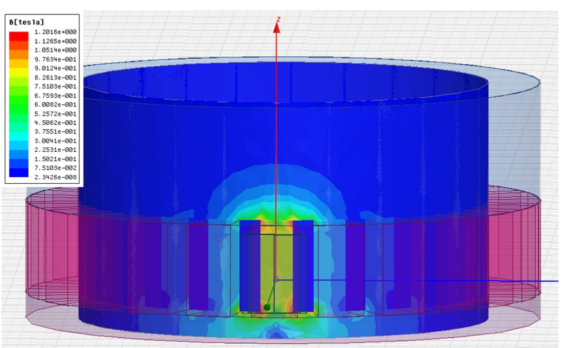


Fig. 10. Flux distribution in a single tooth in FEA model

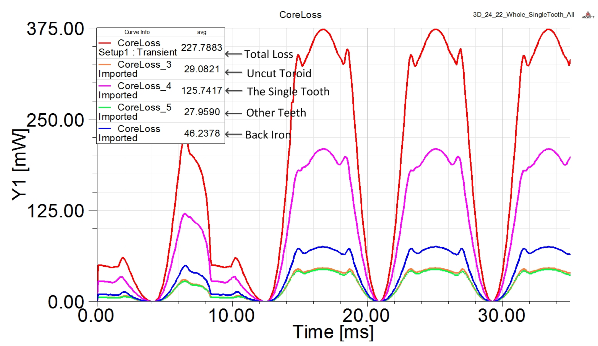


Fig. 11. Loss separation results in FEA model

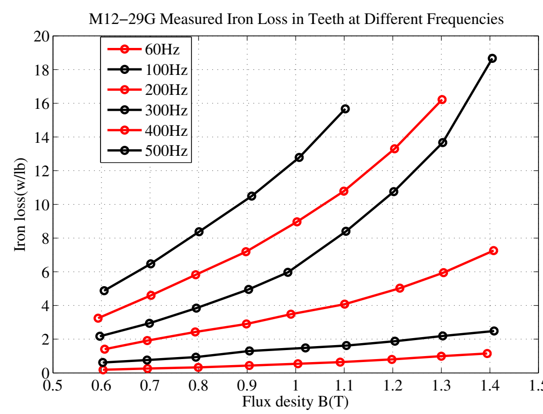


Fig. 12. Estimated core loss data with 55% split in teeth at different frequencies

B. Experiment results for the teeth core loss

The experiment results, manipulated to represent the core loss, of a single tooth at different frequencies and various flux densities are shown in Fig.12. The exact measured loss data with 55% split is shown in Table.I. It can be seen that the core loss in the single tooth is in the range of 2.5 to 4 times higher than that in measured unslotted toroid or back iron.

VI. CONCLUSION

In this paper, a method is proposed to measure the core loss in the back iron and in the teeth of a fabricated stator of a single-sided axial flux permanent magnet machine. FEA simulations are implemented, together with the measured total core loss, to obtain the specific core loss data in the back iron only and in the teeth only. The purpose of these measurement is to try to predict the iron loss as accurately as possible.

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